



**Malin
Space
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Clementine High Resolution Camera Mosaicking Project

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Final Report

submitted by

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INTRODUCTION

This report constitutes the final report for NASA Contract NASW -5054. This project processed Clementine I high resolution images of the Moon, mosaicked these images together, and created a 22-disk set of compact disk read-only memory (CD-ROM) volumes. The mosaics were produced through semi-automated registration and calibration of the high resolution (HiRes) camera's data against the geometrically and photometrically controlled Ultraviolet/Visible (UV/Vis) Basemap Mosaic produced by the U. S. Geological Survey (USGS). The HiRes mosaics were compiled from non-uniformity corrected, 750 nanometer ("D") filter high resolution nadir-looking observations. The images were spatially warped using the sinusoidal equal-area projection at a scale of 20 m/pixel for sub-polar mosaics (below 80° latitude) and using the stereographic projection at a scale of 30 m/pixel for polar mosaics. Only images with emission angles less than approximately 5° were used. Images from non-mapping cross-track slews, which tended to have large SPICE errors, were generally omitted.

The locations of the resulting image population were found to be offset from the UV/Vis basemap by up to 13 km (0.4°). Geometric control was taken from the 100 m/pixel global and 150 m/pixel polar USGS Clementine Basemap Mosaics compiled from the 750 nm Ultraviolet/Visible Clementine imaging system. Radiometric calibration was achieved by removing the image nonuniformity dominated by the HiRes system's light intensifier. Also provided are offset and scale factors, achieved by a fit of the HiRes data to the corresponding photometrically calibrated UV/Vis basemap, that approximately transform the 8-bit HiRes data to photometric units.

The sub-polar mosaics are divided into tiles that cover approximately 1.75° of latitude and span the longitude range of the mosaicked frames. Images from a given orbit are map projected using the orbit's nominal central latitude. Polar mosaics are tiled into squares 2250 pixels on a side, which spans approximately 2.2°. Two mosaics are provided for each pole: one corresponding to data acquired while periapsis was in the south, the other while periapsis was in the north.

The CD-ROMs also contain ancillary data files that support the HiRes mosaic. These files include browse images with UV/Vis context stored in a Joint Photographic Experts Group (JPEG) format, index files ('imgindx.tab' and 'srcindx.tab') that tabulate the contents of the CD, and documentation files. For more information on the contents and organization of the CD volume set refer to the "FILES, DIRECTORIES AND DISK CONTENTS" section of this document.

The Clementine HiRes Mosaic was compiled for the National Aeronautics and Space Administration (NASA) by Malin Space Science Systems personnel under the direction of Dr. Michael C. Malin, principal Investigator. Jeff Warren and Rick Adair comprised the technical group responsible for its compilation.

Much of the background text in this document draws heavily on McEwen et al. [1997].

CLEMENTINE MISSION

The Clementine Mission [Nozette et al., 1994] was a technology demonstration jointly sponsored by the Ballistic Missile Defense Organization (BMDO) and the National Aeronautics and Space Administration (NASA). Clementine was launched on 1994-01-25 aboard a Titan IIG rocket from Vandenburg Air Force Base. The mission included two months of systematic lunar mapping (1994-02-26 through 1994-04-21), which was to have been followed by a flyby of the near-Earth asteroid Geographos (1994-08-31). However, an onboard software error combined with improbable hardware conditions on 1994-05-07 led to accidental spin-up of the spacecraft and loss of attitude control gas. This precluded the flyby of Geographos.

Clementine's primary objective was the qualification of light weight imaging sensors and component technologies for the next generation of Department of Defense spacecraft. A second objective was the return of data about the Moon and Geographos to the international civilian scientific community. For more information on the Clementine Mission refer to the 'mission.cat' file located in the 'catalog' directory on the CD-ROMs.

The HiRes mosaic was created using the Clementine Engineering Data Record (EDR) Image Archive [Eliason, et al., 1995] produced by the Clementine mission. The EDR data are raw images. The archive also includes tabulations of the unprocessed and uncorrected data properties. The Clementine EDR Image Archive contains more than 1.9 million images acquired during active mission operations. For information on how to obtain this archive contact the PDS Imaging Node or visit their world wide web site at the URL: <http://pdsimage.jpl.nasa.gov/PDS>.

HIGH RESOLUTION (HiRes) IMAGING CAMERA

The HiRes camera combined a lightweight beryllium telescope with an image intensifier-coupled frame transfer CCD imager. Image shuttering was accomplished through voltage gating of the image intensifier. Maximum integration time was 733 milliseconds in 10.67 microsecond increments. The spectral response was limited in the system by the S-2 photocathode between 0.4 and 0.8 microns. Five spectral bands were available using a filter wheel that was controlled through the serial-addressable synchronous interface (SASI). A sixth filter position was allocated to an opaque filter for the imager intensifier's protection. Additional information on the HiRes camera is in the 'hresinst.cat' file in the 'catalog' directory on the CD-ROMs.

The post-FPA electronic circuitry was identical to that used in the UV/Vis camera: three gain states were available, followed by 5 bits of offset that spanned 248 counts in the analog regime to augment the basic 8-bit A/D conversion. Images of the Moon's day side used relatively low gain settings and intensifier gate times on the order of 1 ms. Lifetime

concerns about the photocathode and microchannel plates in the intensifier unit drove operations settings to low exposures. This resulted in photon shot noise contributing significantly to the overall noise in the HiRes sensor. Further, the image intensifier imposed a non-uniform, but predictable, artifact within the images.

LUNAR ORBIT SUMMARY

The Clementine spacecraft maintained a polar orbit during the systematic mapping of the surface of the Moon. Mapping of virtually 100% of the lunar surface was accomplished in two lunar days (two Earth months). In order to obtain full coverage during these two months, the required image overlap for the UV/Vis and NIR cameras was ~15% in the down-track and ~10% in the cross-track directions. This required an orbit inclination of $90^\circ \pm 1^\circ$ with reference to the lunar equator, and that the periselene of the orbit be maintained at an altitude of 425 ± 25 km. To provide the necessary cross-track separation for the alternating imaging strips to cover the entire surface of the moon, the orbital period was approximately 5 hours, during which the moon rotated approximately 2.7° beneath the spacecraft. Images were generally taken and recorded only in the region of periselene, leaving sufficient time to replay the data to Earth.

The best data for lunar multispectral mapping is obtained if the solar phase angle is less than 30° . The solar phase angle is defined as the angle between the vector to the Sun and the vector to the spacecraft from a point on the Moon's surface. To maximize the time period in which the solar phase angle is less than 30° , the plane of the orbit should contain the Moon-Sun line half way through the two-month lunar mapping period. Therefore, insertion into orbit was selected so that, as the Moon-Sun line changed with Earth's motion about the Sun, the Moon-Sun line was initially close on the orbital plane, and then in the orbital plane half-way through the mapping mission. The angle between the Moon-Sun line and the orbital plane was close (less than 5°) for approximately five weeks before becoming zero. The table shown below contains a list of Clementine's orbital parameters. For more information on the Lunar orbit refer to the 'mission.cat' file located in the 'catalog' directory on the CD-ROMs.

Clementine Orbital Parameters

Orbital Period:	$4.970 \text{ hr} < P < 5.003 \text{ hr}$
Altitude of Periselene:	$401 \text{ km} < \text{radius} < 451 \text{ km}$
Eccentricity:	$0.35821 < e < 0.37567$
Right Ascension:	$-3^\circ < \Omega < +3^\circ$ (referred J2000)
Inclination:	$89^\circ < i < 91^\circ$
Argument of Periselene:	$-28.4^\circ < w < -27.9^\circ$ (1st month) $29.6^\circ < w < 29.2^\circ$ (2nd month)

GEOMETRIC ACCURACY

The geometric placement of the HiRes mosaics is based primarily on registration with the Clementine Basemap Mosaic, which has accuracies approaching the UV/Vis scale. Thus, an overview of Basemap Mosaic is appropriate.

The UV/Vis Basemap Mosaic

The goal of the UV/Vis basemap was for 95% of the Moon (excluding the oblique observation gap fills) to have better than 0.5 km/pixel absolute positional accuracy and to adjust the camera angles so that all frames matched neighboring frames to within an accuracy of 2 pixels.

Approximately 265,000 match points were collected at the USGS from ~43,000 UV/Vis images, providing global coverage. About 80% of these points were collected via autonomous procedures, whereas 20% required the more time consuming but manual pattern-recognition. Oblique gap-fill images were the most difficult to match, and required substantial human intervention. Matching the polar regions was time-consuming because each frame overlapped many other frames. Most match points were found to a precision of 0.2 pixels.

The USGS match points were sent to the RAND Corporation for analytical triangulations. Using these match points, control points from the Apollo region, and the latest NAIF/SPICE information, RAND determined improved camera orientation angles for the global set of UV/Vis images. A spherical Moon of constant radius (1737.4 kilometers) was assumed, which was a significant source of error near the oblique gap fills. The analytical triangulation is a least-squares formulation designed to adjust the latitude and longitude of the control points and the camera orientation angles to best fit the match points. The final (global) analytical triangulation required solving ~660,000 normal equations. The mean error is less than 1 pixel. This is by far the largest analytical triangulation ever applied to a planetary body other than Earth. The results fully define the planimetric geometry of the basemap, to which future systematic products, including the HiRes mosaic, should be tied.

The HiRes Mosaic

Accurate placement of the map-projected HiRes images was accomplished by combining registration to the UV/Vis basemap at the basemap's resolution (100 m/pixel for sub-polar mosaics and 150 m/pixel for polar mosaics) with registration of overlapping HiRes pairs at five times this resolution (20 m/pixel sub-polar and 30 m/pixel polar). The registrations were facilitated with automated image correlation. These registrations were combined in a Least Absolute Deviation fit (Barrodale and Roberts, 1980) constrained to stray no further than some small amount from the basemap-scale registration. Use of the least absolute deviation gives outliers less importance than does a least squares fit. Further manual

placement of 1-5 percent of the images was required; these were due either to poor initial placement, particularly when the scene was featureless and provided few or no overlapping features with the UV/Vis basemap, or to mismatches of scene, resolution or illumination across seams in the UV/Vis mosaic. Some misregistration of adjacent HiRes images remains in the final mosaic because the paramount goal was registration with the underlying UV/Vis Basemap Mosaic. The HiRes polar mosaics within approximately 2° of the pole were dominantly registered to HiRes images rather than the basemap owing to the lack of useful basemap detail in that region.

RADIOMETRIC UNITS

Absolute photometric calibration of the HiRes image data remains problematic, particularly for the bulk of HiRes images, which were noisy owing to the low gain setting intended to extend the life of the imaging system. For the HiRes mosaics, piece-wise intensity matching of the HiRes mosaics to the UV/Vis Basemap Mosaic was adopted as an approximate radiometric calibration. The further decision was made to use 750 nm ("D") filter HiRes images in order to best match the UV/Vis Basemap Mosaic, which consists dominantly of 750 nm ("B") filter images. A more detailed description of the UV/Vis basemap photometric calibration may be found on the UV/Vis basemap CD-ROM volumes CL_30XX.

HiRes sub-polar mosaic tiles were individually calibrated against the underlying UV/Vis basemap. In contrast, each of the four HiRes polar mosaics employ a single calibration for all tiles because of the generally unreliable calibration of the underlying basemap in shadowed regions. These calibrations are each based on those of well-illuminated tiles and basemap.

In each tile header, the OFFSET and SCALING_FACTOR entries define HiRes fractional reflectances as follows:

$$\text{HIRES MOSAIC FRACTIONAL_REFLECTANCE} = (\text{SCALING_FACTOR} * \text{DN}) + \text{OFFSET}$$

where: DN = 8-bit pixel value of HiRes mosaic image array
 SCALING_FACTOR units are fractional reflectance per DN
 OFFSET units are fractional reflectance

The calibration in every case included correction for the non-uniformity of the raw HiRes images resulting from the light intensifier (M. Robinson, personal communication, 1997).

DATA PROCESSING

Image processing tools developed at Malin Space Science Systems were used for image map projection, registration, tone matching and mosaicking. The USGS program *MapMaker* was used to generate context images from the UV/Vis Basemap Mosaic.

Generally, processing proceeded on an orbit and latitude "bin" basis, reflecting the organization of the Clementine EDR CDs. A latitude bin consists of all images of a given orbit deemed to fall within a 10 degree latitude range based on SPICE information. The latitude ranges are defined to fall on 10-degree boundaries from -90 to +90. For the sub-polar mosaics, sinusoidal map projection of images from a given orbit used the same central longitude, taken to be the orbit's longitude at the lunar equator. Polar mosaics employed the stereographic projection.

The HiRes mosaic was processed in 5 steps:

1. Image calibration, map projection, and basemap generation
2. Low resolution registration
3. HiRes registration
4. Constrained registration
5. Mosaicking and photometric calibration

Step 1

Following radiometric calibration for image non-uniformity (Figure 1), each image was warped to the equal-area sinusoidal or stereographic projection [Snyder, 1982], using the SPICE information in the EDR's PDS header (Figure 2). Only "D" filter (750 nm) images were considered. Images with no apparent content, indicated by MINIMUM = MAXIMUM (DN) header entries, or low intensifier gains (< 10) were rejected. Also rejected were images with excessive emission angles.

The HiRes SPICE information is erroneous to some degree, requiring further effort to register them with the UV/Vis Basemap Mosaic. Both high resolution (20 m/pixel or 30 m/pixel) and low-resolution (100 m/pixel or 150 m/pixel) versions of each image were generated. In the case of the sub-polar mosaic, this necessitated reprojection of the UV/Vis context to match the central longitude of a given orbit's images.

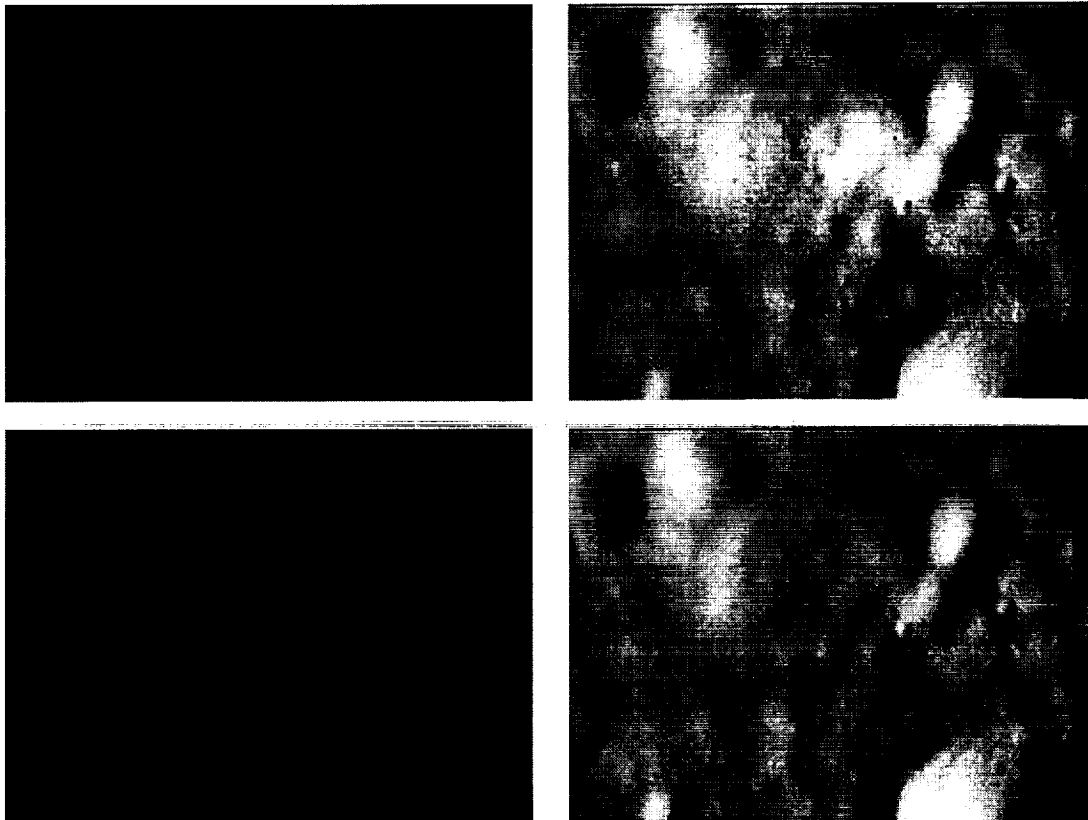


Figure 1:

Raw Image (top left), Raw Image contrast enhanced (Top right)
Non-uniformity corrected (bottom left) and contrast enhanced (bottom right)

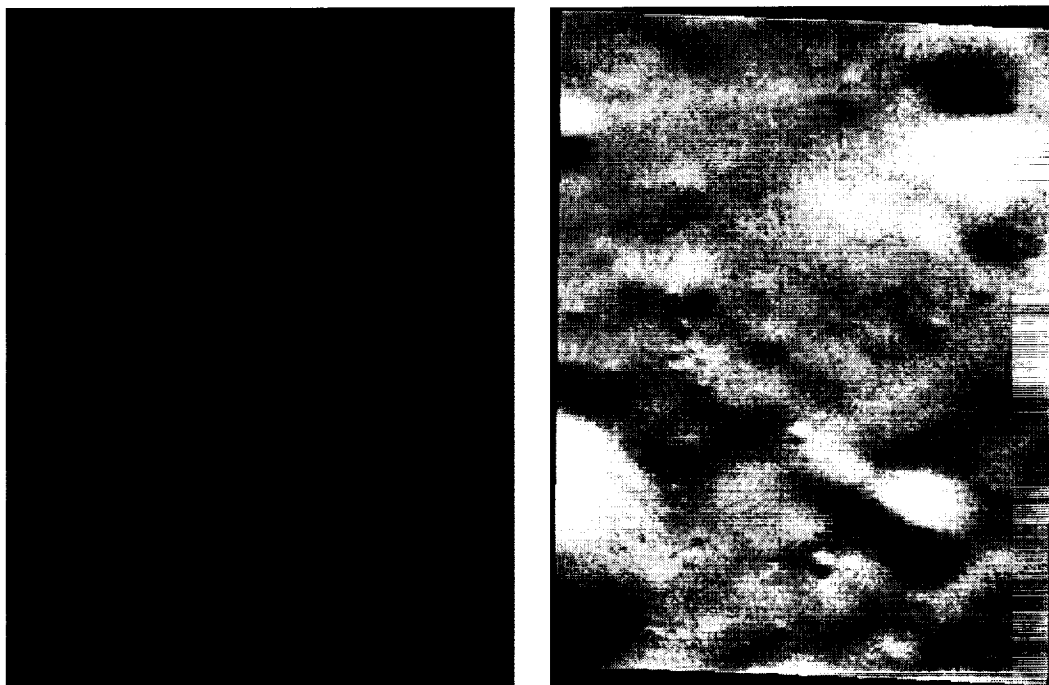


Figure 2:

Map-projected using SPICE information (raw, left; contrast enhanced, right)

Step 2

Step 2 registered the HiRes images at UV/Vis basemap resolution (Figure 3). The HiRes images generally had some small systematic deviation away from a geometrically-controlled position. This deviation was of order 10-200 pixels at 100 m/pixel, tending to be largest near the poles. Correlation of the HiRes images to the UV/Vis basemap permitted HiRes image offsets relative to the UV/Vis basemap to be estimated. Provisional image placements that failed the correlation effort were estimated from neighboring "good" images that did not fail. Very rarely, "holes" in the underlying basemap that arose from the absence of valid UV/Vis data, resulted in sections of HiRes data that lacked geometric constraint to the basemap.

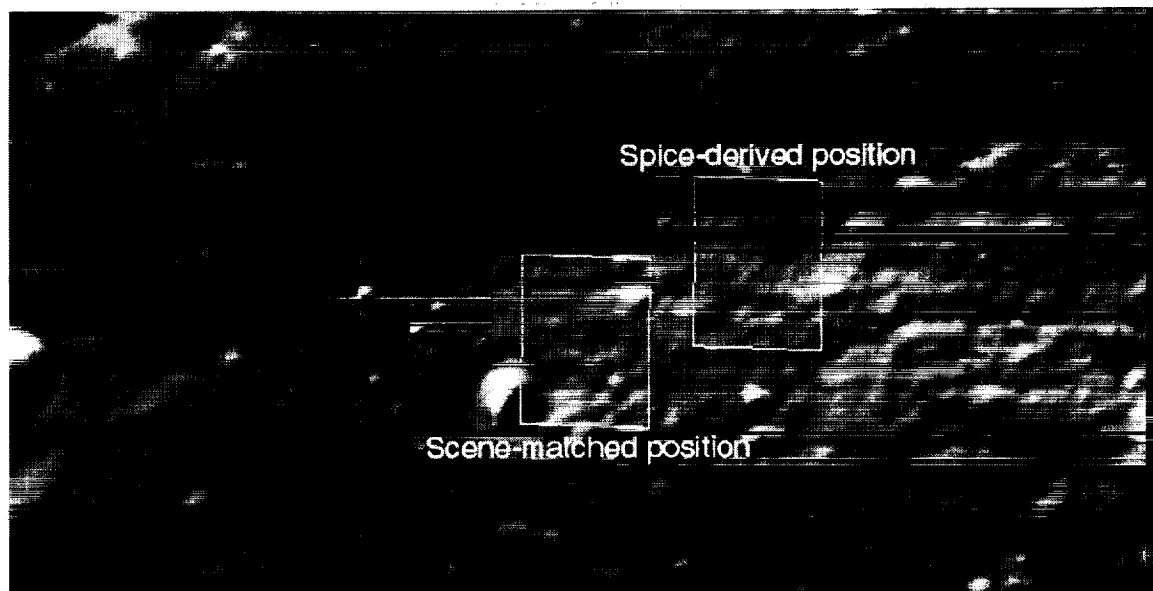


Figure 3: Spice-derived and Scene-matched positions

Step 3

Overlapping "good" images are correlated against each other to provide "full-resolution" placement constraints.

Step 4

The results of the reduced and full resolution registrations were combined to define a constrained, least absolute-deviation problem for image placement. Like the more familiar least-squares fit procedure, this seeks to minimize deviation away from specified targets, in this case the nominal absolute and relative HiRes image placements. However, least-squares tends to weight outlying locations in a manner considered undesirable.

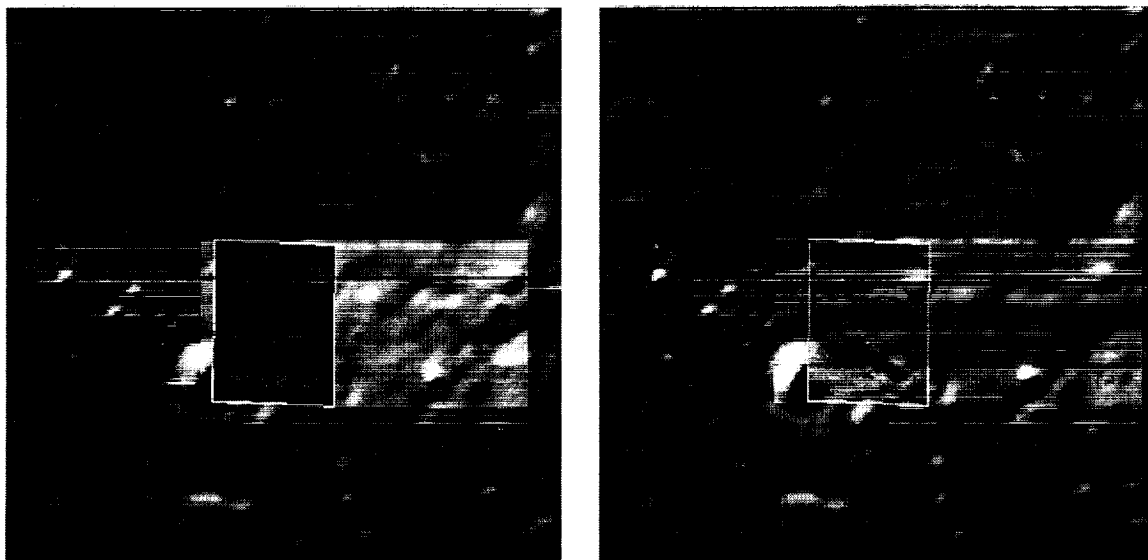


Figure 4: Raw (left) and Brightness-matched (left) Images

An additional constraint was imposed by disallowing any placement solution to stray farther than 3 UV/Vis-resolution pixels from the nominal location. Occasionally, this constraint was relaxed to accommodate relatively severe UV/Vis mosaic seam offsets.

Step 5

Using the estimated placements, the full resolution HiRes images were provisionally mosaicked, laying frames down from south to north. This provisional mosaic was manually examined to detect misplaced or invalid (no significant content) images, the latter resulting from images taken during gain state transitions. Misplaced images were manually mosaicked, and invalid images flagged for exclusion. In regions of great overlap (i.e., near the pole), redundant, poorer-quality data frames were excluded.

Because the UV/Vis Basemap Mosaic is the *de facto* control network for lunar cartography, HiRes images were permitted to mismatch each other when forced to do so by UV/Vis scenes that mismatched across mosaic seams.

Following the manual quality review, a final mosaic was produced as tiles that span approximately 1.75° of latitude for the sub-polar mosaic, and 2250 pixel squares (approximately 2.2°) for the polar mosaics. Low resolution versions with UV/Vis context were also generated to estimate an approximate photometric calibration. The sub-polar calibrations were computed as the least-squares linear fit of the 1.75 -degree tile's DN values to those of the underlying UV/Vis basemap, an 8-bit version generated from the 16-bit versions provided on CD. This chain of linear scalings was then combined to provide a nominal scaling of the tile DNs to physical photometric (fractional reflectance) values. A single calibration was applied to all tiles in each of the four polar mosaics to mitigate problems associated with unreliable basemap calibrations that resulted from

shadows near the poles. The calibrations of the polar mosaics were based on well-illuminated tiles and basemap portions.

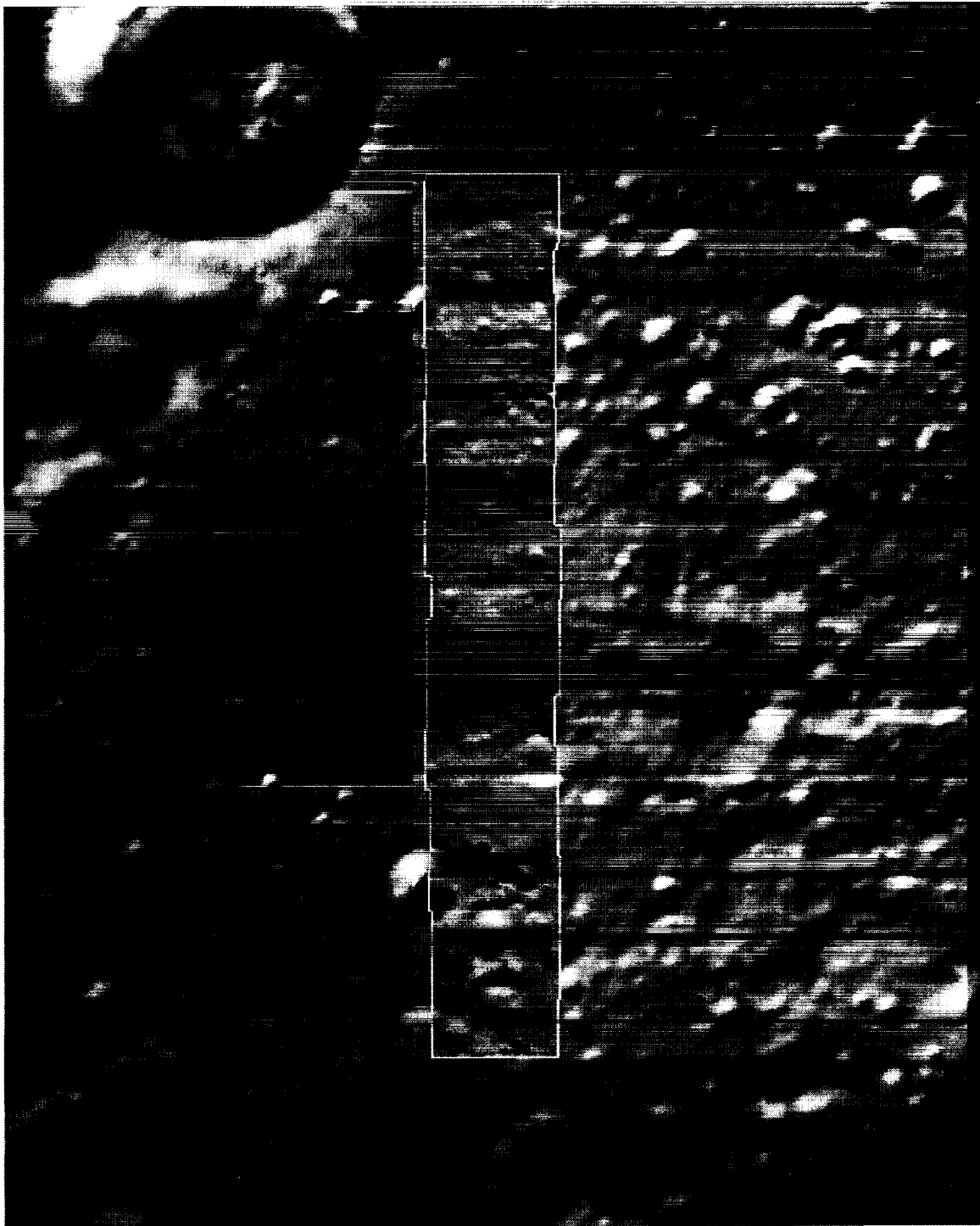


Figure 5: Final Swath

DELIVERY

The deliverable product of this project is a 22 volume set of CD-ROMs that contains the 750-nm "Clementine HiRes Mosaic" of Earth's Moon covering sub-polar latitudes from 80° S to 80° N, and the poles above 80°. The sub-polar mosaics are mapped in the sinusoidal equal-area projection at a resolution of 20 meters per pixel, while the HiRes polar mosaics employ the stereographic projection at a scale of about 30 meters per pixel at the pole.

The sub-polar mosaics are organized into twelve 30-degree wide longitude zones and two latitude zones of 80° extent, which defines 24 grids. This organization mirrors that of the Clementine UV/Vis basemap (CD-ROM volumes CL_3001-3015, available from the PDS), which provides the geometric control for the HiRes mosaics. Generally, the data products from a single grid fill a single CD, although for some longitude zones the data were sparse and the two latitude zones were combined on a single CD.

Figure 6 shows the locations of each sub-polar CD volume. The mosaics of each grid are tiled into convenient strips of approximately 1.75° latitude extent (2653 lines) and widths corresponding to the tile's valid data extent, usually no more than about 300 pixels.

Figures 7 and 8 show the organization of the polar mosaics. The polar mosaics cover latitudes above 80°. The mosaics are divided into square tiles 2250 pixels (approximately 2.2°) on a side, which covers the polar region with 100 (10 by 10) tiles. Two mosaics were generated for each pole: one using data from the north periapsis phase of the mission, the other using data from the south periapsis phase. This yields mosaics of generally uniform resolution, exposure, gain and offset. CD-ROMs 19 and 20 cover the north polar region; 21 and 22 the south polar region.

The image files are organized according to NASA's PDS standards. An image file (tile) consists of a PDS labeled file containing an "image object". Software tools such as ISIS enable users to manipulate such images. ISIS may be obtained from the USGS Astrogeology Branch.

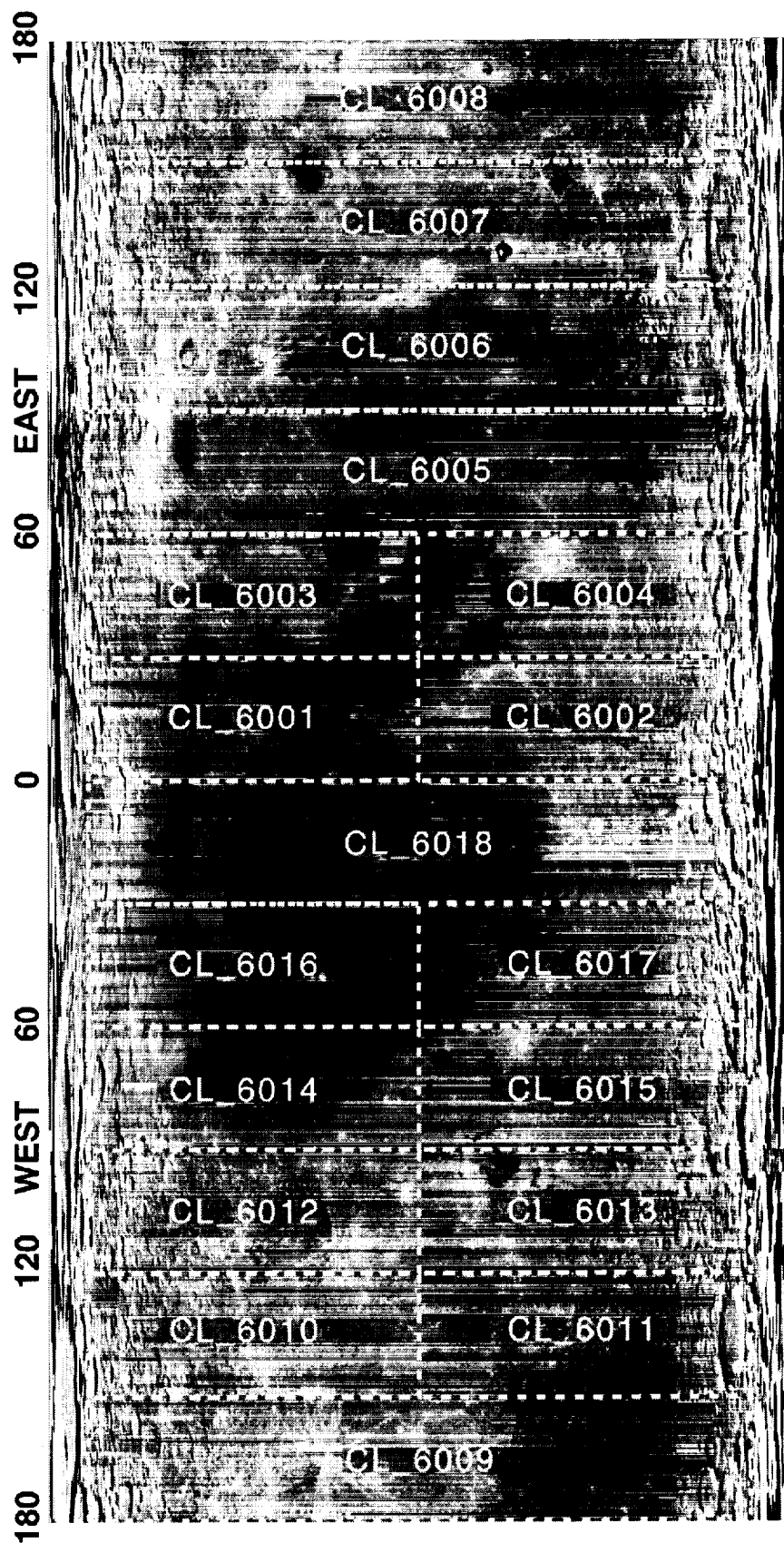


Figure 6: Index to 18 Equatorial and Near-Polar Swath Map CD-ROMs

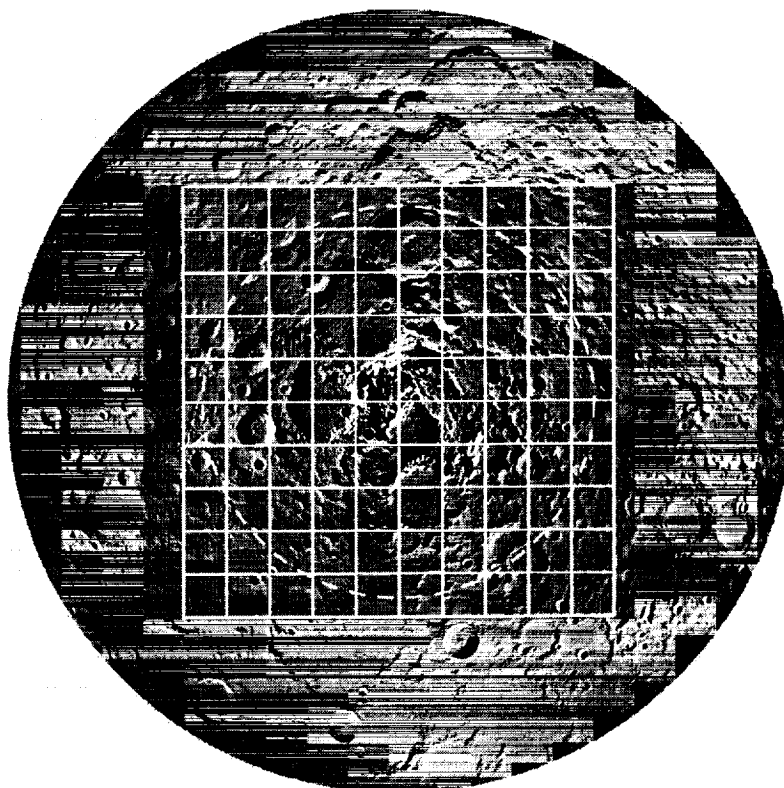


Figure 6: Arrangement of Tiles on North Polar CD-ROMs (19 and 20)

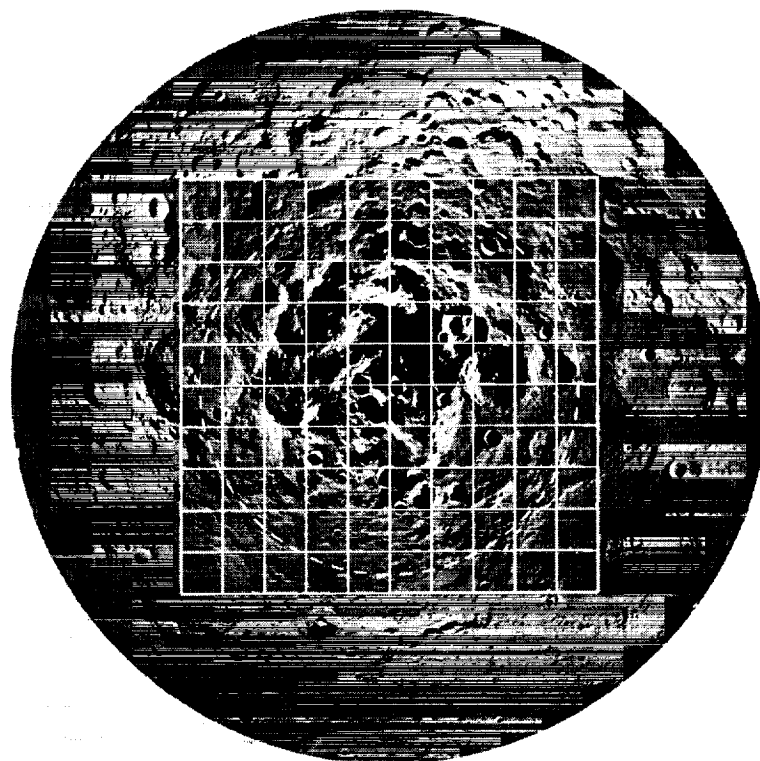


Figure 6: Arrangement of Tiles on South Polar CD-ROMs (21 and 22)

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